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# Estimation of greenhouse gas emissions from road traffic: A case study in Korea

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ABSTRACT

Transport sector is one of the largest greenhouse gas (GHG) emitters worldwide. The majority of GHGs released from this sector is mainly attributed to road vehicles that consume lots of carbon-based fuels every day. The purpose of this study is to estimate the amount of three representative GHGs ($CO_2$, $CH_4$, and $N_2O$) generated by vehicles on major roads in Korea. The Tier 3 method of the Intergovernmental Panel on Climatic Change (IPCC) guidelines has been modified to propose a new simplified estimation model suitable for traffic data available in the country. Three sets of traffic data (Statistical Yearbook of Road Traffic Volume, Statistical Information for Traffic Volume in Highway, and Vehicle Detection System) that cover highways, national roads and local roads have been selected and analyzed to provide activity data for the model. With the suggested methodology yearly GHG emissions have been predicted for the years 2007 and 2008 using both the 2001 and 2005 emission factors suggested by the National Institute of Environmental Research (NIER). Results revealed that most of GHG emissions came from traffic on highways although they are much shorter than national and local roads. It might be due to the several facts that vehicles on highways run at high speeds, and traffic volumes are relatively heavier, and large percentage of trucks has big emission factors.



**Contents**



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## 1. Introduction

Many countries around the globe make various efforts to reduce the greenhouse gas (GHG) that has been regarded as a main cause of global warming and climate change. The primary GHGs released into the Earth's atmosphere are water vapor, carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and ozone. The most recent analysis of the Intergovernmental Panel on Climate Change (IPCC) suggested in its 4th assessment report that a 50–80% reduction of global GHG emissions by 2050 from 2000 levels should be achieved and maintained to prevent any harmful effects of global warming and climate change.

With the goal of achieving the minimization and stabilization of GHGs in the atmosphere, the Kyoto Protocol was adopted on 11 December 1997 in Japan and was entered into force on 16 January 2005 [1,2]. So far, it has been signed and ratified by 191 countries and the so-called obligatory GHG reduction status has been imposed on the developed countries to actively curb the GHG emissions. Nevertheless, the level of GHGs is still high and is not stabilized yet because the amount of obligatory GHG reductions is not enough to catch up with the speed of GHG accumulation. In addition, there are some developing countries generating lots of GHGs that the Protocol has not regulated effectively.

In order to cut down GHG emissions, the characteristics of individual GHGs need to be understood sector by sector so that proper measures can be implemented through efficient resource distribution and management schemes. Among industrial sectors, transport is known to create a large amount of GHGs, accounting for 23% and 22% of entire global GHG emissions in 2005 and 2010, respectively. Korea is known as the top 7 $CO_2$ emitting country in 2010 and 15.4% of total $CO_2$ emissions were from the transport sector. Vehicles on roads are the main contributor to GHG emissions in this sector. The $CO_2$ emissions from road traffic in the world and in Korea in 2010 were 16.4% and 14.5% of total $CO_2$ emissions, respectively [3–6].

The characteristics of GHG emissions from road traffic at urban areas were investigated in a number of countries such as Korea, USA, Spain, Canada, Argentina, Mexico, Romania, Slovakia, Iran, India, and Greece [7–17]. In general, large cities experiences higher GHG emissions from traffic; however, even in relatively small cities, the GHG emissions could be high because of for instance the use of old vehicles and rapid growth in private vehicle [16]. The amounts of GHG emissions from traffic are affected by a large number of variables, for instance, vehicle type, vehicle speed, vehicle age, vehicle acceleration, engine technology, and fuel type [9,11,15–18]. Most studies performed previously on the GHG emissions estimation from road traffic focused on particular areas such as small and large city areas, or on vehicle types and speeds. The GHG emissions from road traffic depending on road types such as highways and local roads should also be of interest.

This study aims to estimate yearly GHG emissions caused by road traffic on major roads including highways, national roads and local roads in Korea. To this end, major traffic data sets were analyzed and key information was obtained for the years 2007 and 2008. These years had marked the substantial increases in the number of registered vehicles in Korea. The Tier 3 of IPCC guidelines has been adopted and modified to propose a simplified GHG estimation model that best utilizes traffic data available in the country. Along with the model, the 2001 and 2005 emission factors developed by the National Institute of Environmental Research (NIER) were used to predict the yearly GHG emissions on highways and national and local roads. The results of this study may help to provide strategic tools for environmentally friendly road constructions and operations, and can be used as a policy source for pursuing low carbon green growth and meeting the Kyoto Protocol requirements. Furthermore, the results of this study may be able to contribute to the successful implementation of Kyoto mechanisms such as the Joint Implementation (JI) and Clean Development Mechanism (CDM), the analysis of emission trading opportunities and the development of GHG reducing technologies that can be applied to individual road types [19–24].

## 2. Review of GHG emissions estimation

### 2.1. The 2006 IPCC guidelines

Depending on the combustion and emission characteristics of individual GHGs, its quantification in transport sector varies. $CO_2$ emissions need to be obtained from the types and quantities of fuels that have different carbon contents, whereas fuel types, operation characteristics, and more complicated emission factors are key information for $CH_4$ and $N_2O$ emission calculations. The 2006 IPCC guidelines present a methodology to calculate the inventories of GHG emission and absorption and have been widely used for the quantification of GHG emissions worldwide. Recommended by countries that participated in the United Nations Framework Convention on Climate Change (UNFCCC) [25], the 2006 IPCC guidelines had been developed and evolved from the 1996 IPCC guidelines, the Good Practice Guidance (GPG) 2000 and the GPG for Land Use, Land Use Change and Forestry (GPG-LULUCF). Members of UNFCCC are largely divided into three groups (1) Annex I including countries that have achieved economic development to some extent by industrialization, (2) Annex II including countries that have obligations to financially support developing countries and transfer technologies to developing countries, and (3) Annex III including other developing countries [1]. Members of UNFCCC have their respective obligations and responsibilities depending on which group they belong to. The 2006 IPCC guidelines are composed of three sub-levels, Tier 1, Tier 2 and Tier 3. Accuracy and precision of the estimations become higher as the level is shifted from Tier 1 to Tier 2 and Tier

3. It is desirable to use an appropriate level considering the contents and forms of data available in each country.

### 2.1.1. Tier 1

Tier 1 is equivalent to the energy sector emission calculation method which obtains the GHG emissions through the multiplication of energy consumption (i.e., fuel consumption) and emission factor. It chooses proper emission factor according to energy source, transport mode and fuel but Tier 1 does not consider the vehicle mileage.

$$Emission = \sum_a [Fuel_a \cdot EF_a] \tag{1}$$

where *Emission* is the emissions of GHGs (kg), $Fuel_a$ is the fuel sold for a given mobile source activity (TJ), $EF_a$ is the emission factor (kg/TJ), and $a$ is the fuel type (e.g., petrol, diesel, natural gas, LPG, etc.).

Here, the emission factor is equal to the carbon content of the fuel multiplied by 44/12. Fuel type ($a$) presented in IPCC needs to be used to choose the right emission factor. GHG emissions are determined by correcting oxidation quotients which are the fraction of carbon stored and the mass ratio between $CO_2$ and C. $CH_4$ and $N_2O$ emissions are determined by multiplying IPCC emission factors by values obtained by converting fuel consumption into energy quantities.

**Table 1**
Methods to calculate GHG emissions in the transport sector of Europe.

| Country | Method | Activity data | Emission factor |
|---|---|---|---|
| Austria | Other model | NS | CS |
| Belgium | Corinair, model, CS | NS | Corinair, CS |
| Denmark | COPERT III | NS | Corinair |
| Finland | IPCC Tier 2 | NS | CS |
| France | Other Model | NS | Other model |
| Germany | IPCC Tier 1 | NS | CS |
| Greece | COPERT III | NS | Corinair |
| Ireland | IPCC Tier 1 | NS | CS |
| Italy | COPERT III | NS, AS | CS |
| Netherlands | IPCC Tier 1 | NS | CS |
| Portugal | Unknown | NS | Unknown |
| Spain | COPERT III | NS, IS | CS |
| Sweden | IPCC Tier 1 | NS | CS |
| England | IPCC Tier 3 | NS | CS |

Note: CS (Country-specific), NS (National statistics), AS (Associations, Business organizations), IS (International statistics).

### 2.1.2. Tier 2

Similar to Tier 1, Tier 2 needs fuel consumption and emission factor as key variables. These variables are function of vehicle class, fuel type, and emission control technology. Tier 2 identifies the emission factor based on GHG and vehicle class that are recommended for use when country specific data are unavailable. It is necessary to have fuel consumption with respect to vehicle class since the emission factor is a function of vehicle class. Tier 2 divides fuel consumption according to the knowledge of similar technologies and samples in order to select the right emission factor.

$$Emission = \sum_{a,b,c} [Fuel_{a,b,c} \cdot EF_{a,b,c}] \tag{2}$$

where *Emission* is the emissions of GHGs (kg), $EF_{a,b,c}$ is the emission factor (kg/TJ), $Fuel_{a,b,c}$ is the fuel consumed (TJ) for a given mobile source activity, $b$ is the vehicle class, and $c$ is the emission control technology (such as uncontrolled, catalytic converter, etc.).

### 2.1.3. Tier 3

GHG emissions can be estimated by travel distance instead of fuel consumption. In order to select the emission factor, Tier 3 resorts to activity data and fuel mix ratio. It provides more accurate GHG estimation than Tiers 1 and 2 but more detailed data are needed on car class and emission control technology to run the model.

$$Emission = \sum_{a,b,c,d} [Distance_{a,b,c,d} \cdot EF_{a,b,c,d}] + \sum_{a,b,c,d} C_{a,b,c,d} \tag{3}$$

where *mission* is the emissions of GHGs (kg), $Distance_{a,b,c,d}$ is the distance traveled (VKT) during thermally stabilized engine operation phase for a given mobile source activity (km), $EF_{a,b,c,d}$ is the emission factor (kg/km), $C_{a,b,c,d}$ is the emissions during warm-up phase (cold start) (kg), and $d$=operating conditions (e.g., urban or rural road type, climate, or other environmental factors).

It is noted that a tier represents a level of methodological complexity involved with the emission estimations. Tier 1 is the basic method, frequently utilizing IPCC-recommended country-level defaults, while Tiers 2 and 3 are each more demanding in terms of complexity and data requirements. If one wants to increase the estimation accuracy, Tiers 2 and 3 might be recommended to use. However, one is not able

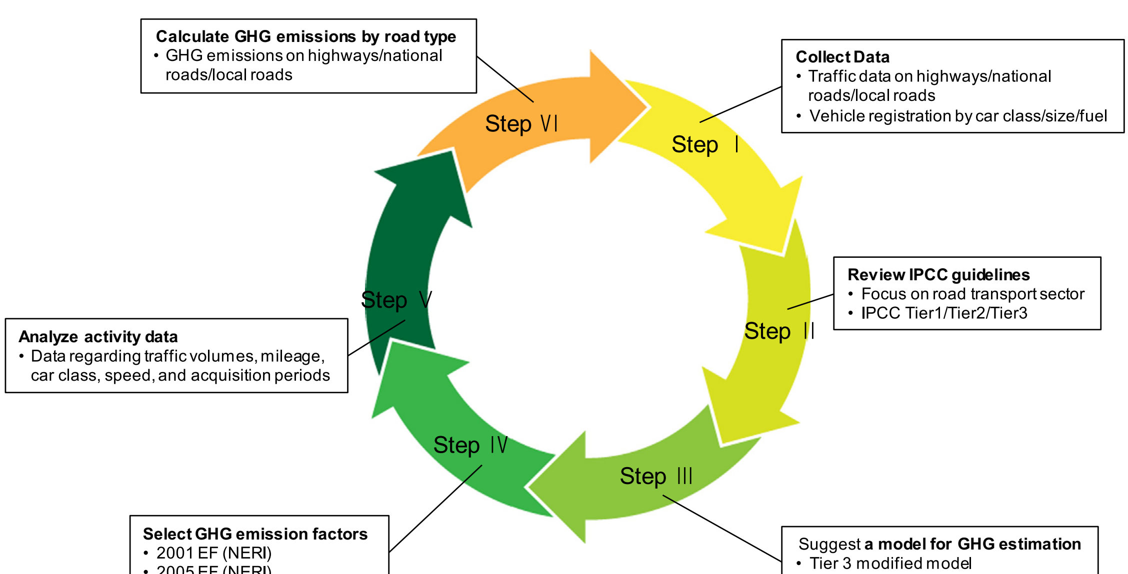


**Fig. 1.** Steps for road transport sector GHG emission estimation.

to make this choice if appropriate emission factors and activity data are not readily available for those Tiers

### 2.2. Current practices for GHG emission predictions by nations

#### 2.2.1. United States

The United States (US) submits national GHG emission statistics to the UNFCCC each year. Although the US basically follows the IPCC guidelines for the estimation of GHG emissions, emission factor and activity data are continuously updated with a series of studies that reflect the variable conditions. Calculations of GHG emissions need fuel consumption data from the Energy Information Administration (EIA) and carbon emission factors of fuels used in the transport sector. Since the carbon emission factors are described as mass per unit energy (Tg carbon/QBtu), the fuels presented in volumes should be converted into masses using densities. In transport, $CO_2$ emissions are determined by multiplying fuel consumption by carbon emission factors of fuels and are then divided based on vehicle class and operating condition. Emission factors for $CH_4$ and $N_2O$ are determined from the results of tests conducted in accordance with Federal Test Procedure (FTP)-75 and corrected using MOBILE 6.2, which is vehicle emission modeling software [26–28]. $CH_4$ and $N_2O$ emissions are separated with respect to transport mode, car class and fuel type.

#### 2.2.2. Europe

Although some countries in Europe use the methods presented in the IPCC guidelines for GHG emissions, many stick to country specific models that are suitable for their circumstances to configure activity data. Both Computer Program to calculate Emissions from Road Transport III (COPERT) [29] and Corinair [30] models developed by the European Environment Agency (EEA) are one of models used in Europe as revealed in Table 1.

COPERT III is a program to calculate mobile contamination source emission factors and emissions. $CO_2$ is classified into Group 2 which consists of substances based on fuel consumption. This is similar to the IPCC Tier 1. In England, GHG emissions are estimated by the Department of Environment, Food and Rural Affairs (DEFRA) using the IPCC Tier 3. $CO_2$ emissions are determined by fuel consumption factors (g fuel/km) of vehicles and average speed factors of vehicles presented in COPERT III.

#### 2.2.3. Japan

Japan Ministry of Environment has determined the GHG emissions based on fuel consumption using the IPCC Tier 1. $CH_4$ and $N_2O$ emissions are organized according to vehicle class, but $CO_2$ emissions are only divided by fuel types. Activity data used for the estimation model include fuel consumption and emission factor [31].

#### 2.2.4. Australia

$CO_2$ emissions have been calculated based on the quantity of fuels using Tier 1. Non-$CO_2$ emissions have been calculated with Tier 2. GHG emissions are estimated in consideration of vehicle class and fuel type. On the other hand, mileage, car registration state, and vehicle′s age have been considered for $CH_4$ and $N_2O$ emissions [32].

## 3. Estimation method for GHG emissions from road traffic

The GHG emission estimation procedure proposed in this study is briefly shown in Fig. 1. In the following sections, tasks conducted in each step are described except for step 2 that is already presented in chapter 2.

**Table 3**
2005 Vehicle emission factor (g/km).

| Vehicle type | | Fuel | $CO_2$ | $CH_4$ | $N_2O$ |
|---|---|---|---|---|---|
| Passenger car | Compact | Gasoline | 137.8 | 0.03 | 0.03 |
| | Small | Gasoline | 180.9 | 0.02 | 0.05 |
| | Medium | Gasoline | 212.9 | 0.02 | 0.06 |
| | Large | Gasoline | 235.7 | 0.02 | 0.04 |
| | Diesel[a] | | 243.3 | 0.00 | 0.01 |
| | LPG | | 231.0 | 0.04 | 0.04 |
| | Others[b] | | | | |
| Taxi | | LPG | 231.0 | 0.04 | 0.04 |
| Van | Small | Gasoline | 251.7 | 0.03 | 0.06 |
| | | Diesel | 243.3 | 0.00 | 0.01 |
| | | LPG | 190.2 | 0.03 | 0.03 |
| | | Others | | | |
| | Medium | Diesel | 315.1 | 0.02 | 0.01 |
| | Large | Diesel | 1382.4 | 0.04 | 0.10 |
| | Special[c] | Diesel | 1375.5 | 0.04 | 0.09 |
| Bus | City | Diesel | 1382.4 | 0.04 | 0.10 |
| | Intercity | Diesel | 1382.4 | 0.04 | 0.10 |
| | Chartered | Diesel | 1382.4 | 0.04 | 0.10 |
| | Express | Diesel | 1382.4 | 0.04 | 0.10 |
| Truck | Small | Gasoline | 247.3 | 0.03 | 0.06 |
| | | Diesel | 245.5 | 0.01 | 0.01 |
| | | LPG | 187.9 | 0.03 | 0.03 |
| | | Others[b] | | | |
| | Medium | Diesel | 334.9 | 0.03 | 0.01 |
| | Large | Diesel | 1388.2 | 0.04 | 0.08 |
| Special class[d] | | Diesel | 812.2 | 0.03 | 0.04 |

[a] Small car run on diesel,
[b] includes alcohol, kerosene, electricity,
[c] emergency and rescue vehicles, and
[d] towing vehicle, tractor-trailer.

**Table 2**
2001 Vehicle emission factor (g/km).

| Vehicle type | GHG Size | $CO_2$ Emission factor | $CH_4$ | $N_2O$ |
|---|---|---|---|---|
| Passenger car | Gasoline | $1177.7V-0.5151$ | $0.4406V-0.7581$ | $0.67V-0.7636$ |
| | LPG | $1397.4V-0.5475$ | $0.7098V-0.8604$ | $1.8768V-1.196$ |
| Bus | Small | $1103.7V-0.413$ | $0.185V-1.0453$ | $0.139V-0.8121$ |
| | Medium | $0.1251V^2-15.385V+646.05$ | $0.2221V-0.6478$ | $0.0522V-0.5206$ |
| | Large | $2804.7V-0.3105$[a] | $0.455V-0.6839$[a] | $2.0311V-0.8501$ |
| | | Others | Others | |
| Truck | Small | $1073.8V-0.4009$ | $0.3796V-0.9561$ | $0.0522V-0.5206$ |
| | Medium | $0.1029V^2-14.937V+798.9$ | $0.4064V-0.6478$ | $0.0522V-0.5206$ |
| | Large | $6240.3V-0.3829$ | $0.402V-0.6197$ | $2.0311V-0.8501$ |

[a] City bus operated on a scheduled service $<50$ km/h.

### 3.1. Data collection

As the first step, traffic data collected and statistically analyzed were reviewed to retrieve activity data on three major road types: highways, national roads and local roads. Data sets reviewed include Statistical Yearbook of Road Traffic Volume (SYRTV), Statistical Yearbook of Ministry of Land, Transportation and Maritime Affairs (SYLTM), Statistical Information for Traffic Volume in Highway (SITVH), Traffic Counting Data (TCD), Freeway Traffic Management System (FTMS), and Vehicle Detection System (VDS). Also vehicle registration, vehicle management records and various survey results on car mileage were taken into account to supplement the data sets [33–49]. Since SYRTV published by Ministry of Land, Transportation and Maritime Affairs (MLTM) every year provides extensive measurements and statistical data on all types of roads in Korea, it was utilized as a main data source for the GHG estimations. Both SITVH and VDS issued by Korea Expressway Corporation (KEC) were also adopted to understand the effect of data sets on the emission estimations especially on highways.

**Table 4**
2008 Vehicle emission factor (g/km).

| Vehicle | Fuel | Emission factor $Y$ | |
|---|---|---|---|
| | | $V < 65$ km/h | $V \geq 65$ km/h |
| Small Van[a] | Diesel | $Y = 1671.3V - 0.5453$ | $Y = 0.7447V + 130.78$ |
| | LPG | $Y = 1862.6V - 0.6044$ | $Y = 0.4717V + 125.54$ |
| Medium van | Diesel | $Y = 1828.9V - 0.4409$ | $Y = 0.2162V + 309.46$ |
| City bus[b] | Diesel | $Y = 3659.4V - 0.3148$ if $V \leq 47$ km/h | |
| | CNG | $Y = 4539.1V - 0.4587$ if $V \leq 47$ km/h | |
| Chartered bus | Diesel | $Y = 2676.7V - 0.3344$ | $Y = 1.3034V + 548.56$ |
| Small truck | Diesel | $Y = 1135.2V - 0.4668$ | $Y = 2.2307V + 25.76$ |

[a] Includes sport utility vehicles, and
[b] needs more data to enhance the accuracy.

### 3.2. GHG emission estimation model

Normally, emissions can be estimated either with fuel consumption or with mileage (i.e., travel distance). According to the

**Table 5**
Characteristics of traffic data sets and activity data by road type.

| | Highway | | | National road | Local road |
|---|---|---|---|---|---|
| Name | SYRTV | SITVH | VDS | SYRTV | SYRTV |
| Provider | MLTM | KEC | KEC | MLTM | MLTM |
| Activity data | Traffic volume | Total mileage | Yearly traffic | Traffic volume | Traffic volume |
| Duration | 1 day | 1 yr | 1 yr | 1 day | 1 day |
| Missing routes | Downtown/military zones | – Open sections<br>– End points to tollgates | BOT routes | Downtown/military zones | Downtown/military zones |
| Travel distance | Available | Not available | Available | Available | Available |
| Vehicle classes | 12 | 5 | N/A | 12 | 12 |

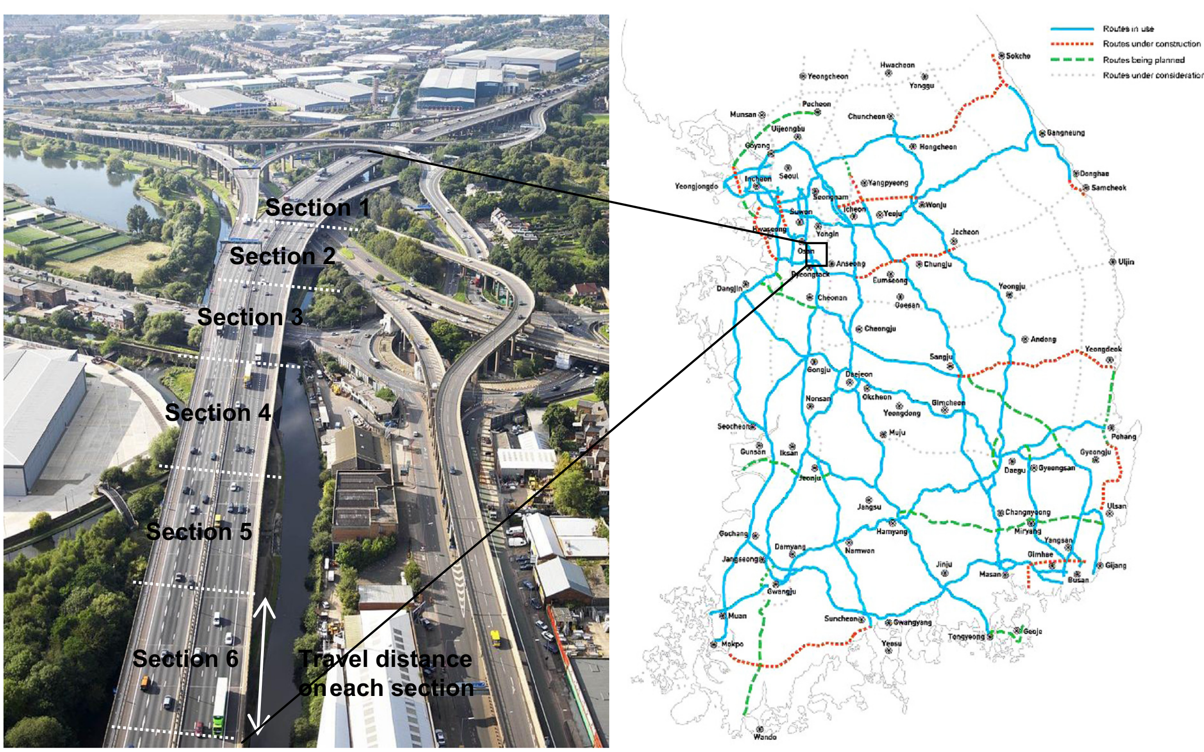


**Fig. 2.** Sections divided on a highway route (images from www.ask.com and www.ex.co.kr).

2006 IPCC guidelines, both Tiers 1 and 2 utilize the former while Tier 3 needs the latter to calculate the emissions. In this study, Tier 3 approach was taken and slightly modified to propose a simpler model as shown in Eq. (4). This model best fits to the conditions of the data sets available and accounts for vehicle classes ($m$) and fuel types ($n$). However, emissions during warming-up (i.e., cold start), emission control technologies, driving conditions and speed variables were not considered in the model.

$$Emission = \sum_{m,n}[VKT_{m,n} \cdot EF_{m,n}] \tag{4}$$

where *Emission* is the emissions of greenhouse gases (kg), $VKT_{m,n}$ is the distance traveled (VKT) per year (km), $EF_{m,n}$ is the emission factor (kg/km), $m$ is the vehicle class, and $n$ is the fuel type (e.g. petrol, diesel, natural gas, LPG, etc.).

### 3.3. Emission factor

Since there are no nationally-certified emission factors in Korea, tentative emission factors developed through a series of investigations by the National Institute of Environmental Research (NIER) have been adopted to run the model. So far three sets of emission factors have been proposed by NIER in 2001, 2005, and 2008. The 2001 emission factor is a function of vehicle speed, and defined for various types, sizes, and fuels of vehicles as presented in Table 2 for three major GHGs, where $V$ is the speed of vehicle. One of drawbacks of it is that one should assume the speed unless real speed data are available [50].

Tables 3 and 4 present the 2005 emission factor. Unlike the 2001 emission factor, this is not a function of speed. Instead, it uses the ratios of vehicle speeds for the emission factor. Therefore, one is able to apply the emission factors without knowing the actual traffic speed [51]. As shown in the Table 4, the 2008 emission factor is based on vehicle speeds, but it did not cover a wide range of vehicle types and size, yielding that some emission factors are not reliable. Also, the 2008 emission factor does not consider the contributions from individual gases. Therefore, this study has adopted both 2001 and 2005 emission factors for the GHG emission estimations [52].

It was assumed that those emission factors do not account for emission control technologies (e.g., catalytic converter) and driving conditions (road types and other environmental factors). Since emission factors were all established on constant speeds, changes in GHG emissions resulting from actual speed variations were difficult to be quantified.

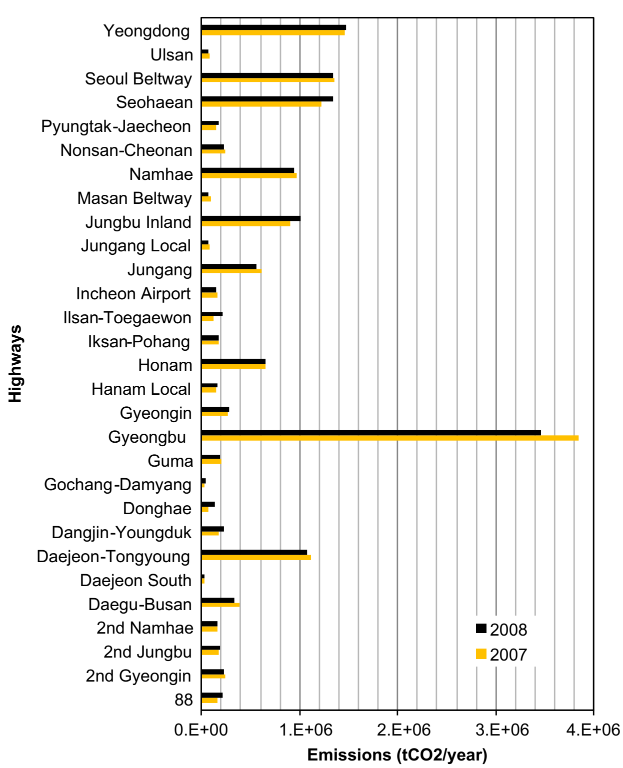


**Fig. 3.** Yearly GHG emissions from highway routes based on SYRTV.

### 3.4. Activity data

Table 5 summarizes SYRTV, SITVH, and VDS representing traffic characteristics on highways, national roads, and local roads. In this study, all three data sets were used for emission predictions on highways whereas activity data from SYRTV were used only for the GHG predictions on national and local roads.

Most of the data were recorded for a full year, except for SYRTV that is built on one day collections each year. There are some routes/sections where traffic data were not collected, such as open toll collection routes/sections, sections from starting/ending points to tollgates, Build–Operate–Transfer (BOT) routes, downtown areas and military zones. Traffic volumes on highways were obtained either from SYRTV or from VDS was used to estimate traffic volumes on national and local roads for those routes/sections. Although each data set has its own vehicle classification system, vehicles had to be reclassified with respect to road occupation ratio of vehicle and fuel type to run the estimation model. Of activity data, travel distance of vehicle was calculated on each route with SYRTV and VDS.

In order to calculate the GHG emissions, total travel distances of individual vehicle classes on each route were multiplied by emission factors, where total travel distances on each route were obtained by adding total travel distances on each section for individual vehicle classes. Fig. 2 shows a conceptual image of how the sections are defined on each route. Total travel distances on each road type (i.e., highways, national roads and local roads) can be obtained by simply adding up total travel distances measured on each route.

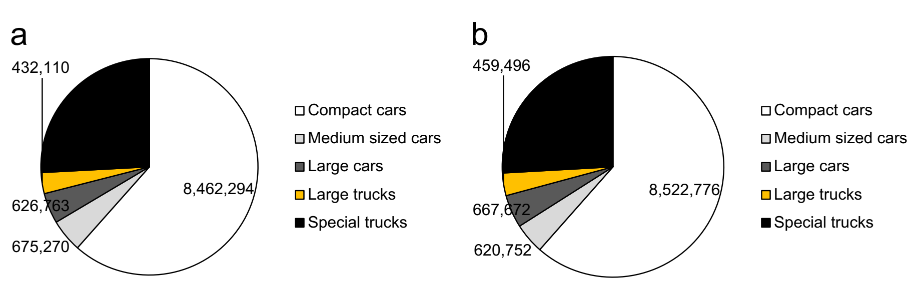


**Fig. 4.** GHG emissions ($tCO_2$) in closed toll sections of highways based on SITVH with 2005 emission factors: (a) 2007, (b) 2008.

For GHG emission from highways, activity data extracted from SYRTV are used for various routes operated by KEC. Emissions from BOT routes are estimated with VDS and the comparison of GHG emissions between open and closed sections can be made with activity data obtained from SITVH.

## 4. Results

### 4.1. GHG emission from highway with the 2005 emission factor

#### 4.1.1. Estimation based on SYRTV

SYRTV contains information about traffic volumes alongside vehicle class, moving direction and time zone for one day (24 h) period at specified sites. Data adopted in this study were collected on the 3rd of October 2007 and 2008, respectively. Most of SYRTV data were automatically collected with Automatic Vehicle Classification (AVC), and some were obtained from manual observations by surveyors. Every car that passed the survey points at each site was categorized according to its vehicle classification system programmed in the collection systems [46,49]. With SYRTV, one can also obtain vehicle mileages for the entire highway routes.

Since SYRTV has only 24 h data, additional data that cover a whole year should be generated to obtain yearly GHG emissions. Therefore, vehicle mileages were multiplied by 365 and vehicles were reclassified based on the occupation ratios such that passenger cars (class 1) were classified into four vehicle sizes (sub compact/compact/midsize/large) and a compact van. Buses (class 2) were classified into midsize and large vans. In addition, pickup trucks (class 3 and class 4) and small trucks (class 3 and class 4) were grouped as small trucks. Class 5∼7 trucks and class 8∼12 trucks were defined as midsize trucks and large trucks, respectively. It was assumed that there were no liquefied petroleum gas (LPG) vehicles on highways and both vans and trucks of mid/large sizes were all diesel powered.

With the 2005 emission factors and Eq. 4, GHG emissions on twenty nine highway routes were calculated as presented in Fig. 3. In total, GHG emissions on highways were 15,260,848 $tCO_2$ in 2007 and15,219,304 $tCO_2$ in 2008. The greatest emission was found on the Gyeongbu, followed by the Yeongdong and Seoul Beltway. This result appears to be affected by the route length to some degree but it is not entirely related. Except for the Gyeongbu (416.0 km), Yeongdong (234.4 km) and Seoul Beltway (128 km) are shorter than Jungang (369.9 km) and Jungbu Inland (265 km). Along with Gyeongbu, both Yeongdong and Seoul Beltway are linked to heavily populated areas and congested with many vehicles, yielding more GHG emissions than Jungang and Jungbu Inland.

#### 4.1.2. Estimation based on SITVH

SITVH has classified cars into five: compact cars (Class 1), midsize cars (Class 2), and large cars (Classes 3, 4, and 5). This vehicle classification system is the same as the one used for toll collections on highways. To apply the emission factors that may cover more diverse vehicles types, vehicles were reclassified using car registration. Vehicle that has the highest occupation ratio was selected as the representative class. As a result, class 1 (small car) was composed of passenger cars (compact/small/medium /large), vans (small), and trucks (compact) and emission factors for passenger (medium and gasoline) cars were applied to this class. Class 2 (medium sized cars) was composed of vans (medium) and trucks (small) and emission factors for trucks (small and diesel) were applied to this class. Class 3 (large cars) was defined to comprise of vans (large) and trucks (small) and emission factors for trucks (small and diesel) were applied to this class. Class 4 (large trucks) covered large trucks and emission factors of medium and diesel trucks were applied to this class. Finally, Class 5 (special trucks) was included large trucks and emission factors of large diesel trucks were applied to this class. Yearly total mileages on highways can be obtained by car classes from SITVH. Traffic volumes by road sections were calculated under the assumption that drivers should use the shortest routes from departure (starting point) to arrival (ending point). Since traffic volumes from starting/ending points to tollgates and on open toll collection sections (i.e., open sections) were obtained SYRTV.

Figs. 4 and 5 illustrate the GHG emissions predicted for closed sections and open sections, respectively, on highways. The total GHG emissions for the closed sections were 13,750,757 $tCO_2$, in 2007 and 13,859,788 $tCO_2$ in 2008, while vehicles have generated 2,534,396 $tCO_2$ in 2007 and 2,606,653 $tCO_2$ in 2008 on open sections. GHG emissions were slightly increased from 2007 to 2008 due to a moderate increase of the number of vehicle registered. Total GHG emissions from the open sections were much smaller than those from closed sections. In both closed and open sections, Class 1 (compact cars) was responsible for most of the GHG emissions while Class 4 (large trucks) generated the least amount of GHG. This is because the number of Class 1 vehicles is quite larger than that of Class 4 vehicles although the emission factor for Class 4 is larger than that for Class 1.

#### 4.1.3. Estimation based on VDS data

Although vehicle mileages on all highways can be calculated using the VDS data collected every day through automatic sensors, traffic volumes are not measured on some routes/sections such as operated under a Build–Operate–Transfer (BOT) system. For those routes/sections, SYRTV has been adopted for assuming traffic volumes. Vehicles were classified by car class division ratios presented in SYRTV because vehicle classes are not identified in VDS data.

Fig. 6 shows the GHG emissions by highways estimated with VDS. Total GHG emissions in 2007 and 2008 were 15,073,250 $tCO_2$ and 16,544,086 $tCO_2$, respectively, indicating GHG emissions increased by approximately 9.7% within a year. It is interesting to note there were some routes where the amounts of GHG

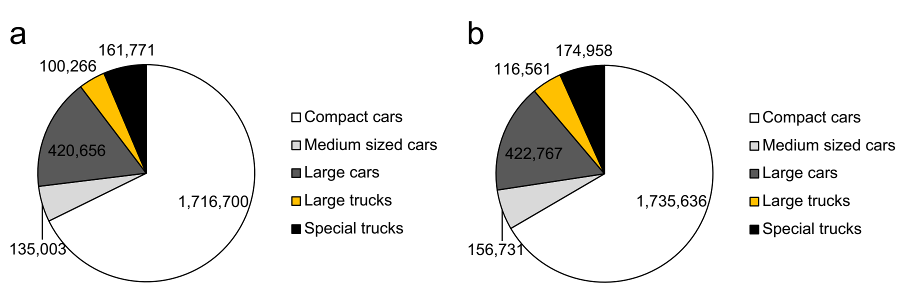


**Fig. 5.** GHG emissions ($tCO_2$) in open toll sections of highways based on SITVH with 2005 emission factors: (a) 2007, (b) 2008.

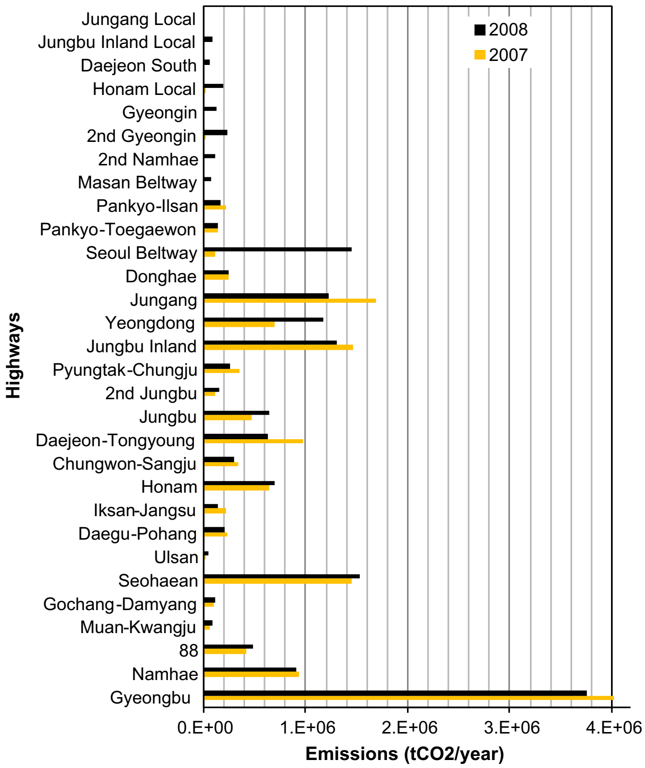


**Fig. 6.** Yearly GHG emissions from highway route based on VDS.

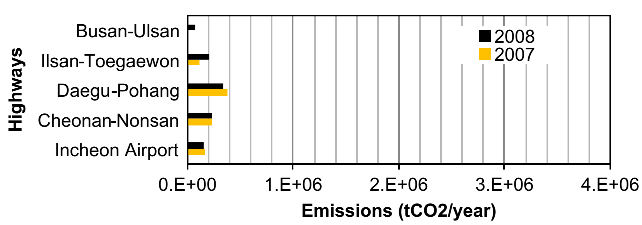


**Fig. 7.** Yearly GHG emissions from BOT routes/sections on highways.

emissions have grown dramatically in 2008. There could be many reasons for this, and increase in traffic volume may be one of them. In fact, traffic lanes of Seoul Beltway and Yeongdong were partially widened to ease heavy traffic during this period, resulting in more vehicles introduced into those routes.

Total GHG emission are similar to those predicted with SYRTV. GHG emissions from the BOT routes/sections were 901,097 $tCO_2$ in 2007 and 995,553 $tCO_2$ in 2008. Individual GHG emissions are displayed in Fig. 7. No emissions on the Busan-Ulsan route were reported because it was fully open to public in 2008.

### *4.2. GHG emissions from national and local roads with the 2005 emission factor*

#### *4.2.1. Emissions from national roads*

SYRTV applicable to national roads is largely composed of two survey methods: random survey and full-time survey. Random survey is conducted occasionally three times a year and observes the traffic at random points, whereas full-time survey is conducted 24 h a day throughout a year at traffic volume count stations. There are some road sections that are not included in those surveys such as unpaved sections, downtown areas and military zones. For those sections measured traffic information from random and full-time surveys was. Car classes were reclassified based on occupation ratios using the car registration states. Passenger cars (class 1) were divided into passenger cars (compact/small/medium sized/large) and vans (small) and buses (class 2) were divided into vans (medium sized/large). Class 3～4 trucks were classified into trucks (small), class 5～7 trucks were classified into trucks (medium sized), and class 8～12 trucks were classified into trucks (large). All vans, medium sized trucks and large trucks were assumed to be diesel cars. Fig. 8 shows the GHG emissions in 2007 and 2008 estimated in entire national roadway routes. It is clearly seen that individual GHG emissions from national roads were much less those from major highway routes. It was found routes 7 and 1 induced relatively large GHG emissions because they were busy roads passing through major cities including Seoul,

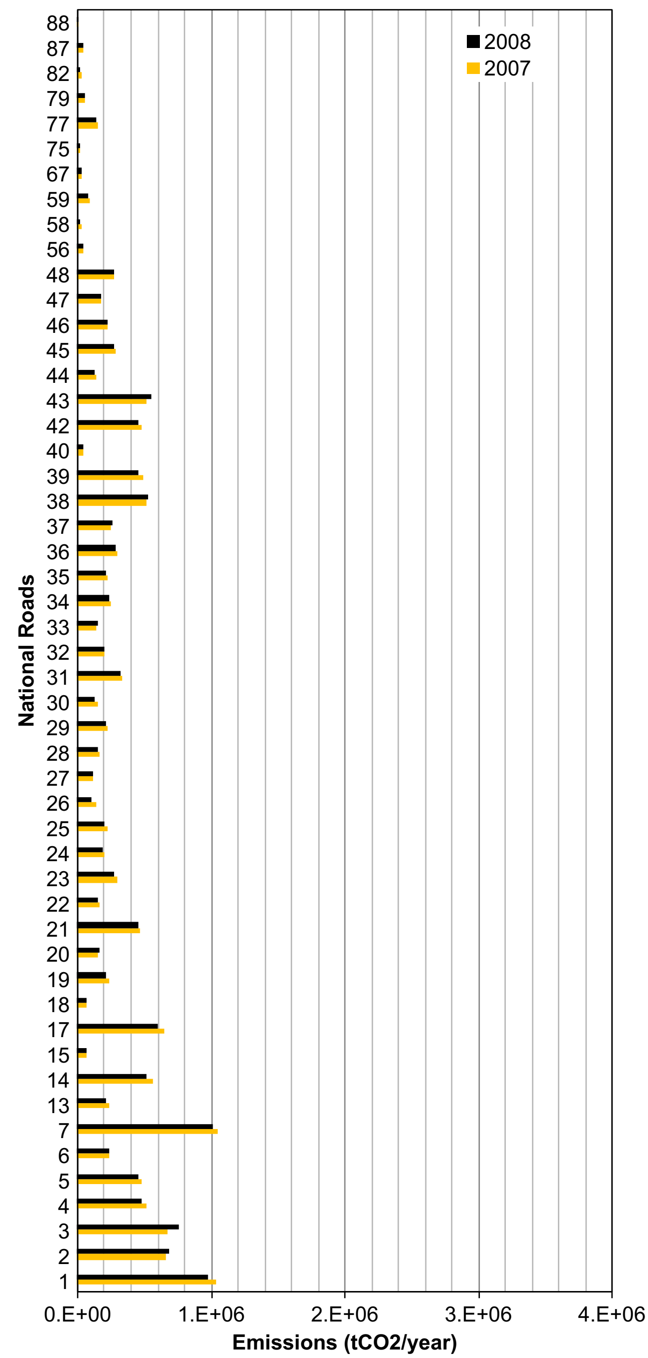


**Fig. 8.** Yearly GHG emissions from national roads.

Suwon, etc. Total GHG emissions were 14,091,090 $tCO_2$ in 2007 and 13,644,194 $tCO_2$ in 2008.

#### 4.2.2. Emissions from local roads

GHG emissions on local roads were calculated with SYRTV and other data necessary for analysis such as vehicle classification and expanded interpretations of traffic volumes were processed in the same manner as used for the national roads. As a result yearly GHG emissions on local roads were 7,529,160 $tCO_2$ in 2007 and 7,601,846 $tCO_2$ in 2008.

### 4.3. GHG emissions estimations with the 2001 emission factor

#### 4.3.1. Highways

In general, the 2001 emission factor cannot be determined without a designated speed. Therefore, four average running speeds (80 km/h, 90 km/h, 100 km/h and 110 km/h) were selected to account for the effect of speeds on GHG emissions. For SITVH and VDS data sets, single emission factors were assumed for the same speed ranges. Vehicles were reclassified according to the occupation ratios using the car registration. Table 6 presents the results. Since $CO_2$ emission factors generally decrease as the speeds increase, GHG emissions were found decreased as average running speed increased up to 100 km/h and then increased slightly at 110 km/h (for SYTRV and VDS data sets). Overall the 2008 emissions were estimated to be slightly larger than the previous year. GHG emissions were slightly larger with VDS data.

#### 4.3.2. National and local roads

Emissions on national and local roads were calculated with SYTRV as shown in Table 7. To utilize emission factors at different speeds, emissions were calculated for average running speeds of 50 km/h, 60 km/h and 70 km/h. It is seen that the total GHG emissions were smaller than those with the 2005 emission factor.

### 4.4. Emissions per road length and mileage

GHG predictions obtained so far can be reanalyzed to understand either the emissions per road length or the emissions per mileage for each road type. Tables 8 and 9 summarize the emissions per road length for national and local roads and highway, respectively. Emission factors were assumed at 50 km/h for simplicity. It is seen that unit GHG emissions on national roads are almost two times larger than those from local roads, but much smaller than those from highways. On highways predictions with VDS data have led to the greatest unit emissions. It appeared the 2001 emission factors induced smaller unit emissions than the 2005 emission factors.

Tables 10 and 11 summarize the GHG emissions per mileage (km•car) for three road types. Similarly the maximum emissions per mileage (km•car) were obtained with the 2005 emission factors in each road type. The largest unit GHG emissions were generated from highway, followed by national road and local road. It might be due to vehicles with larger emission factors that use highways more frequently than national and local roads. This is also supported by the fact that large trucks normally occupy 4.8% of vehicles running on highways, 1.5% on national roads and 0.6% on local roads.

### 4.5. Verification of GHG emission estimation

As one of ways to verify the results, proportion of GHG emissions from highways, national roads and local roads were compared with the ratio of total vehicle mileages to vehicle mileages recorded only on those three major roads. In 2007, Korea Transportation Safety Authority (TS) reported that total travel distances of the registered vehicles were 327,851,659,954 km [44,45] and about 42% (138,935,116,571 km) of them were from highways, national and local roads. At the same year, with the 2005 emission factor, total yearly GHG emissions estimated from three major roads are 36,881,098 $tCO_2$ with SYRTV, 37,905,403 $tCO_2$ with SITVH, and 36,693,500 $tCO_2$ with VDS. Since total yearly GHG emissions from entire road networks were 78,475,668 $tCO_2$ [5], about 47∼48% GHG emissions were from vehicles running on highways, national roads and local roads, suggesting that the method proposed in this study is reasonably accurate. However, predictions with the 2001 emission factor accounted for 35.6% of all emissions. This reveals the 2005 emission factor is more realistic than the 2001 emission factor in estimating the GHG emissions.

**Table 6**
Yearly GHG emissions on highways ($tCO_2$/yr) with 2001 emission factor.

| Speed (km/h) | Year | Data sets for highway | | |
|---|---|---|---|---|
| | | SITVH | VDS data | SYRTV |
| 80 | 2007 | 10,675,170 | 10,851,235 | 10,285,755 |
| | 2008 | 10,799,989 | 11,793,713 | 10,241,396 |
| 90 | 2007 | 10,188,289 | 10,613,546 | 10,039,202 |
| | 2008 | 10,314,821 | 11,520,216 | 10,003,631 |
| 100 | 2007 | 9,818,482 | 10,589,716 | 9,988,219 |
| | 2008 | 9,951,160 | 11,474,871 | 9,963,829 |
| 110 | 2007 | 9,558,521 | 10,771,484 | 10,125,426 |
| | 2008 | 9,701,706 | 11,649,394 | 10,114,743 |

**Table 7**
Yearly GHG emissions on national and local roads ($tCO_2$/yr) with 2001 emission factor.

| Average speed (km/h) | Year | National road | Local road |
|---|---|---|---|
| 50 | 2007 | 11,312,343 | 5,958,356 |
| | 2008 | 10,957,592 | 6,001,878 |
| 60 | 2007 | 10,326,015 | 5,432,947 |
| | 2008 | 10,001,452 | 5,471,576 |
| 70 | 2007 | 9,630,873 | 5,068,016 |
| | 2008 | 9,330,223 | 5,103,713 |

**Table 8**
GHG emissions from unit road length of national and local roads ($tCO_2$/km) at 50 km/h.

| Division | Year | National roads | Local roads |
|---|---|---|---|
| 2005 EF | 2007 | 1109 | 533 |
| | 2008 | 1071 | 536 |
| 2001 EF | 2007 | 890 | 422 |
| | 2008 | 860 | 423 |

**Table 9**
GHG emissions from unit road length of highway ($tCO_2$/km) at 50 km/h.

| Division | Year | Highways | | |
|---|---|---|---|---|
| | | SITVH | VDS | SYRTV |
| 2005 EF | 2007 | 4835 | 4743 | 4542 |
| | 2008 | 4777 | 5088 | 4415 |
| 2001 EF | 2007 | 3170 | 3222 | 3061 |
| | 2008 | 3133 | 3421 | 2971 |

**Table 10**
GHG emissions per unit mileage on national and local roads ($gCO_2$/km•car).

| Division | Year | National roads | Local roads |
|---|---|---|---|
| 2005 EF | 2007 | 262 | 253 |
| | 2008 | 263 | 253 |
| 2001 EF | 2007 | 210 | 201 |
| | 2008 | 211 | 199 |

**Table 11**
GHG emissions per unit mileage on highway ($gCO_2$/km•car).

| Division | Year | Highways | | |
|---|---|---|---|---|
| | | SITVH | VDS | SYRTV |
| 2005 EF | 2007 | 294 | 294 | 289 |
| | 2008 | 294 | 289 | 290 |
| 2001 EF | 2007 | 192 | 200 | 195 |
| | 2008 | 193 | 194 | 195 |

## 5. Summary and conclusions

This paper presents the estimations of transport sector GHG emission on highways, national roads and local roads in Korea. To this end, a new GHG emission model that is based on the multiplication of travel distance and emission factor has been developed and three traffic data sets were collected and analyzed to predict the yearly GHG emissions. Based on the GHG emission prediction for the years 2007 and 2008, the following conclusions can be drawn:

1. With the 2005 emission factor GHG emissions on highways were 16,285,152 $tCO_2$, 15,974,347 $tCO_2$ and 15,260,848 $tCO_2$ based on the SITVH, VDS data, and SYTRV respectively in 2007, which were slightly lower than estimations for 2008: SITVH (16,466,441 $tCO_2$), VDS data (17,539,640 $tCO_2$), and SYTRV (15,219,304 $tCO_2$).
2. With the 2005 emission factor GHG emissions produced by traffic were about 14,091,090 $tCO_2$ on national roads and 7,529,160 $tCO_2$ on local roads in 2007, and 13,644,194 $tCO_2$ on national roads and 7,601,846 $tCO_2$ on local roads in 2008
3. Based on 2007 traffic data, it was found that 20.7% of GHG emissions were from highways, 18.0% from national roads and 9.6% from local roads.
4. The GHG emissions on highways, national roads and local roads calculated in this study were verified with the travel distances of vehicles. As a result the 2005 emission factor was found more realistic in estimating the GHG emissions than the 2001 emission factor.

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